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COMBUSTION EXPERIMENTS WITH NORTH DAKOTA LIGNITE

BY

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COMBUSTION EXPERIMENTS WITH NORTH DAKOTA LIGNITE.

By Henry Kreisinger, C. E. Augustine, and W. C. Harpster.

INTRODUCTION.

The Bureau of Mines is conducting an extensive investigation of methods of burning different fuels under power-plant boilers and in house-heating furnaces, with a view to effecting improvement of the methods or equipment, thus decreasing waste and promoting a more efficient utilization of fuel resources. Some of the publications that the bureau has issued on the economical use of coal are Technical Paper 80, "Hand Firing Soft Coal Under Power-Plant Boilers"; Technical Paper 97, "Saving Fuel in Heating a House"; Technical Paper 137, "Combustion in the Fuel Bed of Hand-Fired Furnaces"; Technical Paper 139, "Low-Rate Combustion in Fuel Beds of Hand-Fired Furnaces"; Technical Paper 180, "Firing Bituminous Coals in Large House-Heating Boilers"; Technical Paper 199, "Five Ways of Saving Coal in Heating Houses"; and Bulletin 135, "Combustion of Coal and Design of Furnaces."

This paper gives the results of combustion tests of North Dakota lignite burned in two forms—natural lignite as it comes from the mine and the carbonized residue from gas retorts. The tests were made by burning the fuels at various rates in experimental furnaces and by studying the processes of combustion. The information thus obtained was used in determining some of the general principles on which a successful furnace can be developed for use under power-plant boilers and for house-heating apparatus. A small furnace of this character was designed and tested with promising results. All the experiments were conducted in the fuel-efficiency laboratory of the Bureau of Mines, at Pittsburgh, Pa.

THE NATURAL LIGNITE.

The natural lignite came from Lehigh, N. Dak. It was mined and brought to Pittsburgh in the spring of 1909 and was stored in a quantity of about 20 tons piled on the ground and covered with a layer of soil about 4 inches thick. This covering prevented weathering and disintegration, so that when, in 1917, the lignite was uncovered it appeared to be in the same condition as it was when taken

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out of the mine. The analyses of the lignite made in May, 1909, soon after the shipment was received, and those made in 1917, after eight years of storage, are given in the following tables:

TABLE 1.—*Analysis of lignite in May, 1909.*

	As received.	Moisture free.	Moisture and ash free.
Proximate analysis:			
Moisture per cent	40.23	....	....
Volatile matter do.	24.89	41.64	47.03
Fixed carbon do.	28.03	46.90	52.97
Ash do.	6.85	11.46	....
	100.00	100.00	100.00
Ultimate analysis:			
Hydrogen do.	7.03	4.28	4.83
Carbon do.	37.45	62.66	70.77
Nitrogen do.	.42	.70	.79
Oxygen do.	47.63	19.86	22.44
Sulphur do.	.62	1.04	1.17
Ash do.	6.85	11.46	....
	100.00	100.00	100.00
Calorific value:			
Calories	3,470	5,806	6,557
British thermal units	6,246	10,451	11,803

TABLE 2.—*Analysis of lignite in August, 1917.*

	As received.	Moisture free.	Moisture and ash free.
Proximate analysis:			
Moisture per cent	34.88	....	....
Volatile matter do.	26.57	40.80	47.23
Fixed carbon do.	29.69	45.59	52.77
Ash do.	8.86	13.61	....
	100.00	100.00	100.00
Ultimate analysis:			
Hydrogen do.	6.70	4.33	5.01
Carbon do.	40.79	62.64	72.51
Nitrogen do.	.58	.89	1.03
Oxygen do.	42.61	17.82	20.63
Sulphur do.	.46	.71	.82
Ash do.	8.86	13.61	....
	100.00	100.00	100.00
Calorific value:			
Calories	3,658	5,617	6,502
British thermal units	6,584	10,111	11,704

The natural lignite is of brown color and has a distinct woody structure. When exposed to the weather, the lignite dries and crumbles into small flat pieces or flakes. Similar crumbling also takes place, to a large degree, in the fire, and is the chief source of trouble in burning lignite, because the small crumbled pieces sift through the grate and are lost in the ashes.

THE CARBONIZED RESIDUE.

The carbonized residue was a charge drawn from a city gas-plant retort, and was furnished by E. J. Babcock, dean of the school of mines of the University of North Dakota. The residue consisted of small pieces, all of them passed through a ½-inch screen, and 44 per cent through a ⅛-inch screen with square meshes. The material was dull gray, almost black, and its specific weight was 0.8, that of anthracite coal of similar size. The results of an analysis were as follows:

TABLE 3.—*Analysis of carbonized residue.*

	As received.	Moisture free.	Moisture and ash free.
Proximate analysis:			
Moisture per cent	14.46	....	....
Volatile matter do	8.96	10.47	12.03
Fixed carbon do	65.49	76.57	87.97
Ash do	11.09	12.96	....
	100.00	100.00	100.00
Ultimate analysis:			
Hydrogen do	2.64	1.20	1.38
Carbon do	68.84	80.49	92.47
Nitrogen do	.76	.89	1.02
Oxygen do	16.12	3.82	4.39
Sulphur do	.55	.64	.74
Ash do	11.09	12.96	....
	100.00	100.00	100.00
Calorific value:			
Calories	5,771	6,747	7,752
British thermal units	10,388	12,145	13,954

METHOD OF TESTING THE FUELS.

The natural lignite was tested in the following ways:

(*a*) By burning it in a small laboratory furnace with the object of studying the processes of combustion in the fuel bed when the fuel was burned at the rates of 3, 6, 10, 20, 40, and 60 pounds of fuel per square foot of grate per hour. The tests were made with fuel beds 6 inches and 12 inches thick.

(*b*) By burning in a hand-fired furnace provided with a long combustion chamber. These tests were made with the object of studying the process of combustion in the gases rising from the fuel bed. Tests were made at the rates of combustion of 35, 46, and 60 pounds of coal per square foot of grate per hour, with the fuel bed 6 inches thick.

(*c*) By heating small cubes of the lignite in a small furnace and determining the rate of heating and observing the changes in appearance.

(*d*) By burning the lignite in a small furnace specially designed for burning this kind of fuel.

The carbonized residue was tested in the following ways:

(*e*) By burning it in the same furnace and at the same rates as was the lignite in test (*a*), but with fuel beds 4 and 6 inches thick.

(*f*) By burning it in the same special furnace, with the sloping grate as was the lignite in test (*d*).

SUMMARY OF CONCLUSIONS.

In ordinary furnaces North Dakota lignite is difficult to ignite. In a burning fuel bed the lignite disintegrates into small flakes, which pack closely on the grate, so that a comparatively high draft is required to force air through the fuel bed and the fire tends to burn through in spots. The partly burned flakes sift readily through an ordinary grate, causing high ash losses. The carbon in the lignite seems to be very active in combining with O_2 and CO_2. In the first 1 to 3 inches of the fuel bed the carbon burns to CO_2; above this layer the CO_2 is rapidly reduced to CO, so that at the top of the fuel bed the gases contain practically no oxygen and only a very small proportion, frequently less than 1 per cent, of CO_2. On account of the almost complete reduction of CO_2 the surface of the fuel bed with ordinary rates of combustion is nearly black, a fact that partly accounts for the difficult ignition.

The rate of distillation of the volatile content is nearly uniform over the entire firing cycle, and as the volatilized matter is mostly light gases it is easier to avoid the production of objectionable amounts of smoke in burning lignite than in burning Pocahontas coal.

The carbonized residue packs closely on the grate and the fire requires high draft, which causes uneven burning. The fire is nearly dark at the surface because of the almost complete reduction of CO_2 to CO, which is a heat-absorbing process. The freshly fired carbonized residue is rather difficult to ignite because of the low temperature at the surface of the fuel bed.

The experiments indicate that the lignite and its carbonized residue might be burned successfully on an inclined step grate with an arch extending from the bridgewall over almost the entire length of the grate. The arch turns the flames and the hot gases back over the incoming fuel, thus aiding ignition. It also directs air admitted at the bridgewall against the fuel bed and increases the rate of combustion.

TESTS (SERIES *a* AND *e*) MADE FOR STUDYING COMBUSTION IN FUEL BED.

DESCRIPTION OF FURNACE.

The furnace used in the series *a* and series *e* tests is described in detail in Technical Paper 137.[a] A section through the furnace is shown in figure 1. The furnace was provided for taking simultaneous samples of gases from the fuel bed at distances of 1½, 3, 4½, and 6 inches above the grate. Temperature could also be measured at these points.

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[a] Kriesinger, Henry, Ovitz, F. K., and Augustine, C. E., Combustion in the fuel bed of hand-fired furnaces. Tech. Paper 137, Bureau of Mines, 1917, pp. 15–16.

In order to prevent the sifting of combustible matter into the ashpit, special grates, shown in figure 2, were used.

Grate 1 (fig. 2) was of specially shaped steel bars. The air spaces were about ½ inch wide and their walls made an angle of 37° with the plane of the grate. The angle of the air spaces effectively prevented the sifting of small pieces of combustible through the gate.

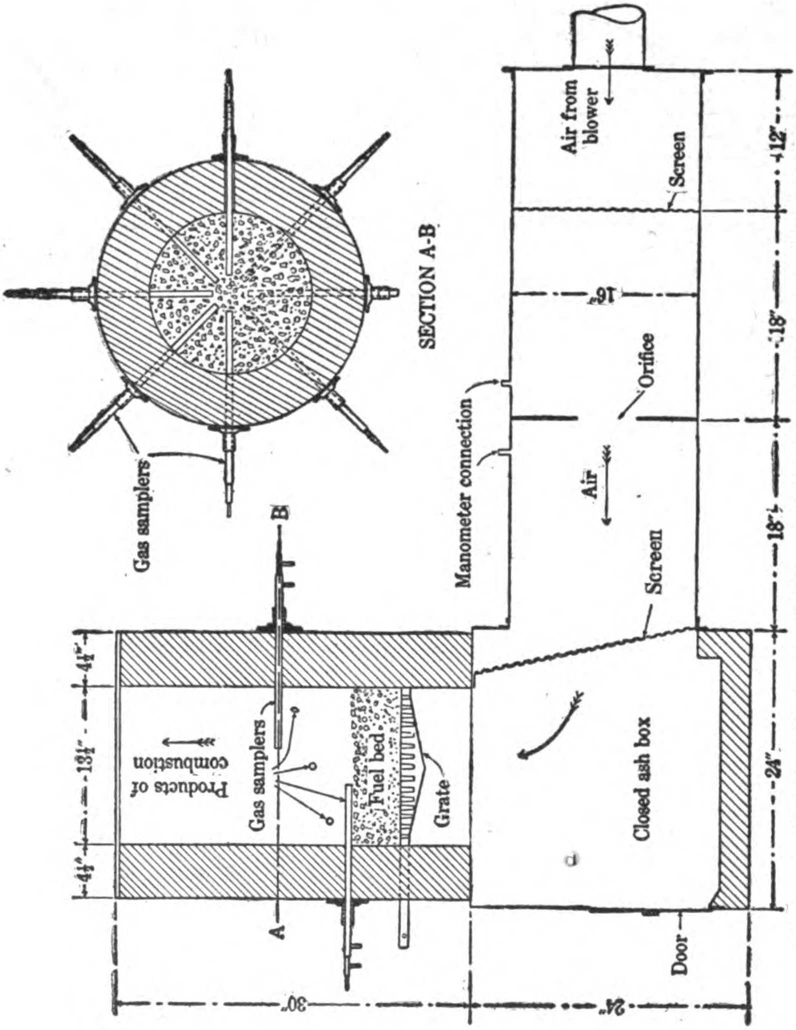

FIGURE 1.—Experimental furnace used for studying the process of combustion in fuel bed.

Grate 2 (fig. 3) was a perforated steel plate $\frac{3}{16}$ inch thick, with ¼-inch round holes spaced ⅝ inch center to center.

Grate 3 (fig. 4) was a slotted steel plate $\frac{3}{16}$ inch thick, with $\frac{3}{16}$-inch slots, separated by strips ⅜ inch wide.

METHOD OF CONDUCTING THE TESTS.

Each test lasted 1 to 2 hours, the fuel being fired in small quantities every 3 to 10 minutes. During each test samples of gases were taken from the fuel bed for each 1½-inch interval above the grate. The samples were collected with water-cooled samplers inserted through the openings in the furnace wall, as shown in figure 1. The temperatures were measured only approximately with a Haskin

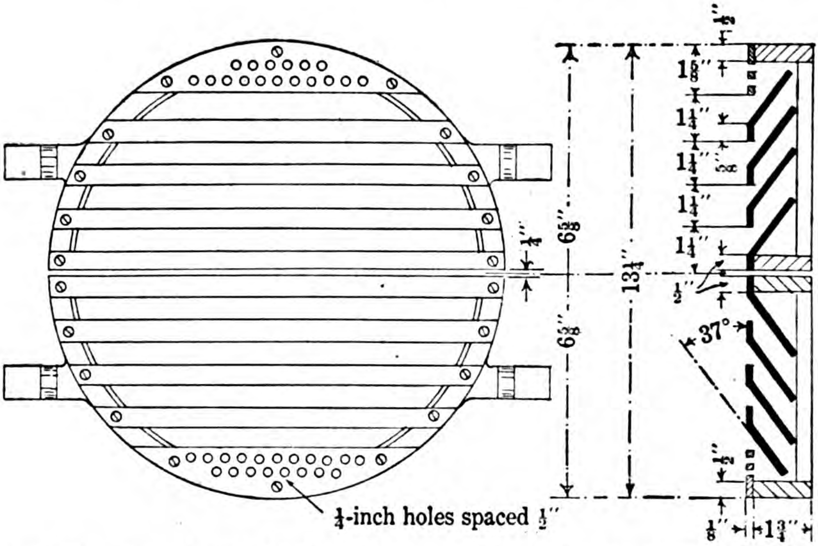

FIGURE 2.—Type of grate (No. 1) used in the experimental furnace shown in figure 1.

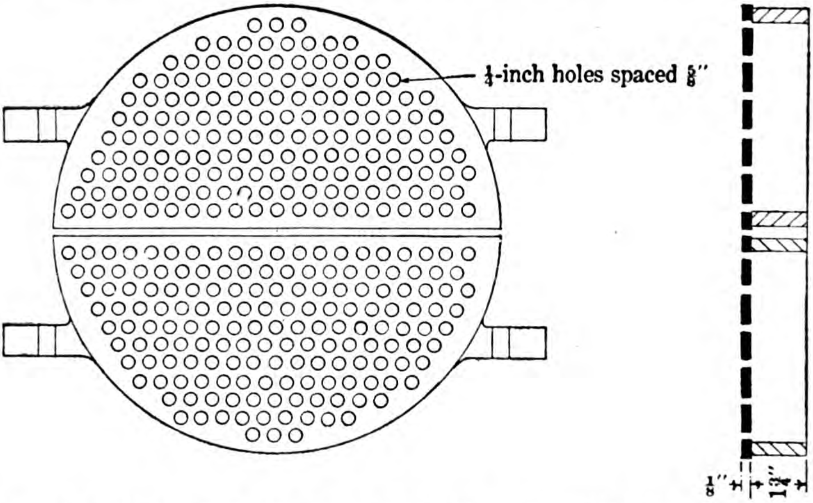

FIGURE 3.—Another type (No. 2) of grate used in experimental furnace.

thermocouple inserted through the sampling holes into the fuel bed. When the temperature reached 1,000° C., the couple was pulled out to save it from destruction. In all such instances the temperature is stated as being above 1,000° C. The pressure of the air passing through the fuel bed was determined with a U-tube draft gage.

For these tests the natural lignite was broken and sized, and the pieces that passed through a 2-inch and over a ½-inch square-mesh screen were used.

NOTES ON TESTS WITH LIGNITE.

With rates of combustion of 3 and 6 pounds per square foot of grate per hour, the surface of the fuel bed was almost entirely black. The flames were 6 to 12 inches long, were yellow, and not sooty.

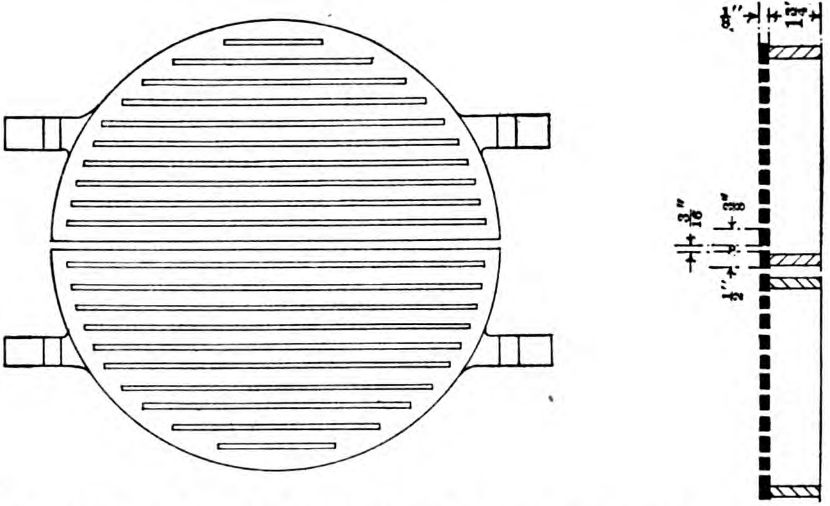

Figure 4.—Third type (No. 3) of grate used in experimental furnace.

With rates of combustion of 10 and 20 pounds, the surface of the fuel bed was dull red. The flames were 2 to 4 feet long, and were clear yellow.

The rates of 40 and 60 pounds made a hot fire with clear yellow flames several feet long.

The fire was left over night with an orifice 2.1 inches in diameter open to the ash pit, but with no air pressure. Next morning, after about 16 hours, forced draft was put on and the fire started in a few minutes.

With the rates of combustion not exceeding 10 pounds no clinker, or only a very small amount, was made. With rates of combustion of more than 20 pounds, dense and impervious clinker formed on the grate.

NOTES ON TESTS WITH CARBONIZED RESIDUE.

With rates of combustion of 3 to 10 pounds, the surface of the fuel bed remained black. The fire showed a decided tendency to form air channels and to burn faster in spots where the channels were formed. These spots were especially evident along the furnace walls, where the resistance to the passage of air through the fuel bed was lower than near the center of the grate. The burning spots were indicated by a dull red surface and bluish flames 2 to 6 inches long. In order to reduce this tendency for faster burning along the wall, the surface of the fuel bed was dished and made somewhat thicker near the wall than it was in the center. The fuel did not burn satisfactorily on a flat grate at these low rates of combustion.

With a rate of combustion of 20 pounds, the surface of the fuel bed was black in places and the fire tended to burn in spots, particularly along the furnace wall. The flame was about 2 feet long and spread over the entire surface of the fuel bed. There were many sparks, formed by particles of burning fuel passing up with the gases. The burning of this fuel on a flat grate at this rate of combustion is not satisfactory. Apparently it is difficult to make the air supply to flow through the fuel bed uniformly over the entire grate surface.

With a rate of combustion of 40 pounds, the fuel bed was strongly agitated and the mass of the fuel appeared to be moving like a boiling liquid. The top of the fuel bed was of a uniform bright-red color and emitted yellow flames several feet long. Sparks were carried up by the gases in considerable quantity. This rate of combustion was apparently the best for burning such fuel on a horizontal grate.

With a rate of combustion of 60 pounds the fuel bed was agitated too violently and large quantities of cinder was carried away by the blast. The flames were several feet long and were yellow and violet. Evidently such a rate of combustion was entirely too high for this kind of fuel.

With a rate of combustion of 20 pounds and with all higher rates the flame had a characteristic yellow and violet color, with practically no red in it. A person's face exposed to the light from the flame appeared ghostly pale with violet or almost black lips and eyelids. Very likely this characteristic color was due to the sodium and potasium salts in the fuel.

With rates of combustion of more than 10 pounds the ash showed a decided tendency to melt and form solid and impervious clinker, covering the grate completely but not adhering to it. The formation of clinker is a serious drawback to burning this type of fuel on a horizontal grate. These remarks hold true for 4-inch as well as for 6-inch fuel beds.

With a circular opening 1 inch in diameter in the ash pit, and no air pressure, the fire kept about 14 hours, showing that in house-heating furnaces the fire could be kept over night.

RESULTS OF TESTS.

The composition of gases in the fuel bed and other data collected during the tests are given in Tables 4 and 5.

TABLE 4.—*Results of tests of natural lignite, made for studying combustion in fuel bed.*

[Size of lignite lumps, ½ to 2 inches.]

Test No.	Thickness of fuel bed.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Temperature in fuel bed.	Weight of air per pound of combustible, computed from analysis.	Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.
						Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	Inches.	*Minutes.*		*Pounds.*	*Inches.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	° *C.*	*Pounds.*	*Grams.*	*Grams.*
121	6	95	0.02	3.8	1½	10.9	0	0.0	14.9	0	0.8	73.4	15.7	740	....	....	....
	....	....	....	....	3	4.8	0	0.0	24.3	0	1.7	69.2	26.6	750	5.1	....	....
	....	....	....	....	4½	10.5	0	2.0	12.9	.3	2.6	71.7	15.8	670	6.9	....	....
	....	....	....	....	6	2.7	0	17.5	0.4	0	.1	79.3	.5	550	56.1	....	....
	....	....	....	....	7½	2.9	0	17.5	0.1	0	0	79.7	.1	....	....	....	....
120	6	80	.05	6	1½	6.6	0	0.0	22.7	0.1	0.9	70.2	23.2	865	....	....	....
	....	....	....	....	3	4.7	0	0.0	26.9	0.2	3.3	64.9	30.4	840	4.5	....	....
	....	....	....	....	4½	6.9	0	8.6	11.4	0.2	2.0	70.9	13.6	810	8.4	0.192	0.057
	....	....	....	....	6	5.8	0	14.1	1.1	0.0	0.2	78.8	1.3	620	25.1	0.013	0.006
	....	....	....	....	7½	5.5	0	14.6	0.4	0.0	0.0	79.5	0.4	....	....	0.004	0.000
122	6	60	.10	10	1½	6.9	0	0.2	22.1	.1	.8	69.9	23.0	Over 1,000	....	....	....
	....	....	....	....	3	0.6	0	0	32.5	.1	2.1	64.7	34.7	920	4.3	....	....
	....	....	....	....	4½	3.8	0	.6	26.8	.5	4.8	63.5	32.1	....	4.5	0.079	0.070
	....	....	....	....	6	7.3	0	9.2	6.4	.2	1.5	75.4	8.1	830	11.9	0.050	0.028
	....	....	....	....	7½	7.5	0	12.3	0.2	.0.	0.1	79.9	0.3	785	....	0.003	0.013
123	6	36	.26	20	1½	1.0	0	0	32.2	0	1.5	65.3	33.7	Over 1,000	....	....	....
	....	....	....	....	3	.4	0	.1	32.1	.1	2.6	64.7	34.0	Over 1,000	4.4	....	....
	....	....	....	....	4½	1.9	0	0	30.1	.1	5.0	62.9	35.2	....	4.3	0.031	0.08
	....	....	....	....	6	5.3	0	0	27.7	.2	10.8	56.0	38.7	....	3.7	0.260	0.06
	....	....	....	....	7½	10.6	0	0	16.3	.1	5.8	67.2	22.2	....	....	0.087	0.06
124	6	30	.50	40	1½	15.1	0	0.5	10.0	.0	.3	74.1	10.3	Over 1,000	....	....	....
	....	....	....	....	3	0.1	0	0.2	33.7	.0	1.2	64.8	34.9	....	4.2	....	....
	....	....	....	....	4½	0.1	0	0.1	32.8	.1	3.4	63.5	36.3	....	4.2	0.024	0.057
	....	....	....	....	6	7.1	0.7	0.6	23.4	.2	7.9	60.1	32.2	....	4.2	0.236	0.084
	....	....	....	....	7½	11.4	0	1.6	13.1	.9	3.0	70.0	17.0	....	....	0.051	0.046

125	6	20	1.00	60	1½									Over 1,000			
					3	0.4	0	0.2	32.8	0	1.1	55.5	33.9		4.3		
					4½	0.5	0	0.0	32.0	.2	1.6	65.7	33.8		4.4		
					6	3.6	0	0	28.7	1.2	7.1	59.4	37.0		3.9		
					7½	9.8	0	0	18.0	1.1	4.8	66.3	23.9				
126	11	120	.12	7.0	1½	11.3	0	0.1	13.1	0.2	1.2	74.1	14.5				
					3	4.4	0	0.1	24.7	0.1	2.4	68.3	27.2	Over 1,000	5.1		
					4½	5.0	1.7	0.1	25.8	.3	6.8	60.3	34.9		4.3		
					6	8.8	0	0.5	25.0	.5	7.0	58.2	32.5		3.7		
					7½	7.6	0	0.0	24.9	.4	9.3	57.8	34.6				
					9	8.9	0.3	0.3	26.0	.4	9.2	54.9	35.9			0.378	0.042
					10½	6.8	0.4	8.7	10.3	1.5	5.4	66.9	17.6		7.7	0.192	0.012
					12	8.4	0	9.4	4.0	0.1	1.7	76.4	5.8		13.4	0.043	0.020
127	12	30	.85	20	1½	7.5	0	1.1	19.8	0.2	1.1	70.3	21.1				
					3	10.4	0	3.4	10.0	.3	.3	75.6	10.6				
					4½	0.1	0	0.2	31.0	.2	8.9	59.6	40.1		4.2		
					6	1.1	0	0.2	29.4	.4	9.3	59.6	39.1		4.2		
					7½	2.7	0	.4	26.6	.1	6.1	64.1	32.8				
					9	4.7	0.1	.0	26.7	.5	1.5	56.55	38.8		3.9	0.373	0.070
					10½	5.0	0	.2	27.8	1.3	16.7	49.0	45.8		3.1	0.423	0.043
					12	11.3	0	4.6	6.5	.1	0.5	77.0	7.1		9.5	0.056	0.033
					13½												
128	12	18	2.6	40	1½	0.6	0	20.0	0.2	0.0	0.1	79.1	0.3				
					3	0.7	0	19.8	0.2	0.0	0.0	79.3	0.2				
					4½	1.2	0	0.1	31.3	0.2	1.0	66.2	32.5		4.5		
					6	3.4	0	0.4	28.2	0.3	1.6	66.1	30.1		4.6		
					7½	7.9	0	0.5	20.8	0.2	2.3	68.3	25.3				
					9	5.7	0	0.1	25.9	0.7	5.2	62.4	31.8		4.2	0.333	0.047
					10½	4.8	0	0.3	27.7	0.9	11.3	55.0	39.9		3.6	0.153	0.889
					12	5.4	0	0.1	27.8	1.0	10.8	54.9	39.6		3.5	0.207	0.108
					13½												
129	11	30		60	1½	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
					3	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
					4½	0.5	0.0	0.0	33.0	0.1	2.8	63.6	35.9		4.2		
					6	11.4	0	1.6	11.8	0.0	1.7	73.5	13.5		7.0		
					7½	9.7	0	1.5	16.1	0.4	2.9	70.4	18.4				
					9	8.1	1.2	.2	21.2	0.2	8.2	60.9	30.8			0.032	0.103
					10½	5.4	0.1	2.6	21.7	0.7	6.9	62.6	29.4		4.9	0.043	0.156
					12	8.3	0	1.8	18.4	0.4	6.5	64.6	25.3		5.2	0.040	0.167
					13½												

[a] Air samples.

TABLE 5.—*Results of tests of carbonized lignite made for studying combustion in fuel bed.*

Test No.	Thickness of fuel bed.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Temperature in fuel bed.	Weight of air per pound of combustible computed from analysis.
						Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	Inches.	*Minutes.*		*Pounds.*	*Inches.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	° *C.*	*Pounds.*
116	4	60	0.12	3	1½	10.4	0	0.3	13.9	0.1	1.1	74.2	15.0	855	8.5
					3	0.8	0	0.1	30.8	0.0	1.4	66.9	32.2	725	5.9
					4½	7.8	0	10.5	2.7	0.0	1.4	78.6	3.0	670	21.0
114	4	60	.18	6	1½	2.9	0	0.1	28.8	0.1	1.5	66.6	30.3	825	5.9
					3	0.9	0	0.0	32.3	0.1	2.2	64.5	34.6	885	5.9
					4½	9.5	0	8.9	3.7	0.0	0.3	77.6	4.0	735	16.5
115	4	42	.37	10	1½	10.6	0	0.4	16.0	0.1	0.9	72.0	17.0	Over 1,000.	7.6
					3	0.2	0	0.1	33.0	0.1	3.4	63.2	36.8	975	5.3
					4½	4.8	0	1.3	23.5	0.3	3.7	66.4	27.4	825	6.5
117	4	48	1.10	20	1½	3.5	0	0.1	28.1	0.1	1.2	67.0	29.3	Over 1,000.	5.9
					3	0.3	0	0.1	33.8	0.0	1.1	64.7	34.9	do.	5.3
					4½	0.2	0	0.1	32.7	0.2	4.0	62.8	36.8	870	5.5
118	4½	18	2.3	40	1½	12.3	0	2.1	9.2	0.0	0.4	76.0	9.6	....	9.9
					3	0.1	0	0.0	33.1	0.1	1.2	65.5	34.5	....	5.5
					4½	2.4	0	0.2	29.3	0.1	3.0	65.0	32.3	....	5.7
119	4½	10	3.1	6.0	1½	2.4	0	17.7	1.0	0.0	0.1	78.8	1.1	....	65.0
					3	1.3	0	0.0	31.3	0.1	1.4	65.9	33.0	....	5.3
					4½	4.1	0	1.0	25.3	0.3	2.8	66.5	28.3	....	6.3
110	6½	80	.22	3.7	1½	11.3	0	0.3	15.4	0.1	0.7	72.2	16.1	780	....
					3	6.6	0	0.0	22.8	0.1	1.0	69.5	23.8	760	6.6
					4½	4.5	0	0.4	23.4	0.1	1.1	70.5	24.5	740	7.1
					6	4.8	0	0.1	24.0	0.1	1.5	69.5	25.5	770	4.0
					7½	7.9	0	9.2	5.3	0.0	0.6	77.0	5.9	....	....

109	6	60	.37	6.0	1½	8.3	0	0.1	19.7	0.1	1.0	70.8	20.7	870	....
	....	....	....	....	3	2.6	0	0.1	28.7	0.1	1.3	67.2	30.0	845	6.0
	....	....	....	....	4½	0.9	0	0.1	32.2	0.1	1.3	65.4	33.6	770	5.5
	....	....	....	....	6	0.5	0	0.1	31.8	0.1	2.2	65.3	34.1	....	5.7
	....	....	....	....	7½	9.3	0	0.6	3.9	0.0	0.1	78.1	4.0	....	....
108	6	120	.55	10.0	1½	4.1	0	0.0	27.1	0.0	1.2	67.6	28.3	965	....
	....	....	....	....	3	0.1	0	0.4	33.7	0.1	1.3	64.4	35.0	990	5.3
	....	....	....	....	4½	0.1	0	0.3	33.4	0.1	2.4	63.7	35.4	930	5.3
	....	....	....	....	6	0.6	0	0.4	32.4	0.1	4.0	62.5	36.4	755	5.3
	....	....	....	....	7½	9.2	0	0.4	5.1	0.1	0.7	76.5	5.8	....	....
111	6½	40	1.8	20.9	1½	3.7	0	0.1	27.8	0.1	1.1	67.2	28.9	Above 1,000.	....
	....	....	....	....	3	0.2	0	0.2	34.1	0.2	1.9	63.4	36.0	...do....	5.0
	....	....	....	....	4½	0.4	0	0.2	33.6	0.0	2.8	63.0	36.8	...do....	5.2
	....	....	....	....	6	0.4	0	0.2	33.1	0.1	3.6	62.6	36.8	...do....	5.2
	....	....	....	....	7½	1.4	0.1	0.1	32.2	0.1	3.2	62.9	35.5	....	....
112	6½	30	3.9	44.0	1½	3.2	0	0.1	29.6	0.0	1.0	66.1	30.6	Above 1,000.	....
	....	....	....	....	3	3.2	0	0.1	28.0	0.5	0.9	67.3	29.3	...do....	5.9
	....	....	....	....	4½	2.8	0	0.2	28.6	0.1	2.1	66.2	30.7	...do....	5.9
	....	....	....	....	6	1.4	0	0.1	31.5	0.3	2.5	64.2	33.6	...do....	5.4
	....	....	....	....	7½	1.4	0	0.0	30.8	0.4	3.8	63.6	34.7	....	....
113	6½	24	4.3	60.0	1½	5.2	0.0	0.0	25.4	0.2	0.9	68.3	26.8	....	....
	....	....	....	....	3	6.5	0	10.8	5.7	0.1	0.4	76.5	6.2	....	17.4
	....	....	....	....	4½	8.5	0	0.1	18.1	0.1	1.7	71.5	19.8	....	7.5
	....	....	....	....	6	10.6	0	0.5	13.7	0.2	1.7	73.3	15.6	....	8.4
	....	....	....	....	7½	7.6	0	0.1	15.8	0.2	2.3	74.0	18.3	....	....

DISCUSSION OF RESULTS OF TESTS.

TESTS WITH NATURAL LIGNITE.

The combustion process in a 6-inch fuel bed of lignite burned at various rates of combustion is shown graphically in figure 5. Each group of curves represent a different rate of combustion.

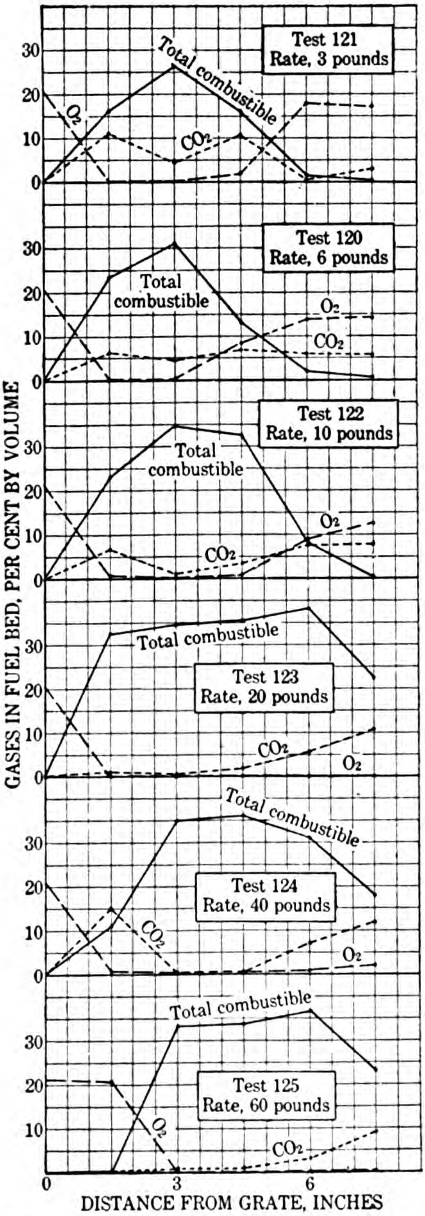

FIGURE 5.—Composition of gases in 6-inch fuel bed of natural lignite when burning at rates of combustion of 3, 6, 10, 20, 40, and 60 pounds per square foot of grate per hour.

The curves show a rapid disappearance of free oxygen, and the rapid and nearly complete reduction of CO_2 to CO. These results seem to indicate that great readiness of the carbon to combine with O_2 or CO_2 is a property characteristic of lignite.

TESTS WITH CARBONIZED RESIDUE.

The process of combustion in the fuel bed of the carbonized residue is shown graphically by the curves of figure 6. The figure shows 12 separate groups of curves, each group representing one rate of combustion. The groups at the left represent tests with 6-inch fuel beds and those at the right, tests with 4-inch fuel beds. Each group shows the percentage of oxygen (O_2), carbon dioxide (CO_2) and total combustible gases in the fuel bed at different distances from the grate.

The most noteworthy feature shown by the curves is the complete disappearance of free oxygen at a point 1½ inches above the grate. For the tests with the rate of combustion of 60 pounds per square foot of grate per hour the points are erratic because the burning fuel moved so violently that channels formed in the fuel bed, permitting the oxygen to penetrate higher. At the surface of the fuel bed

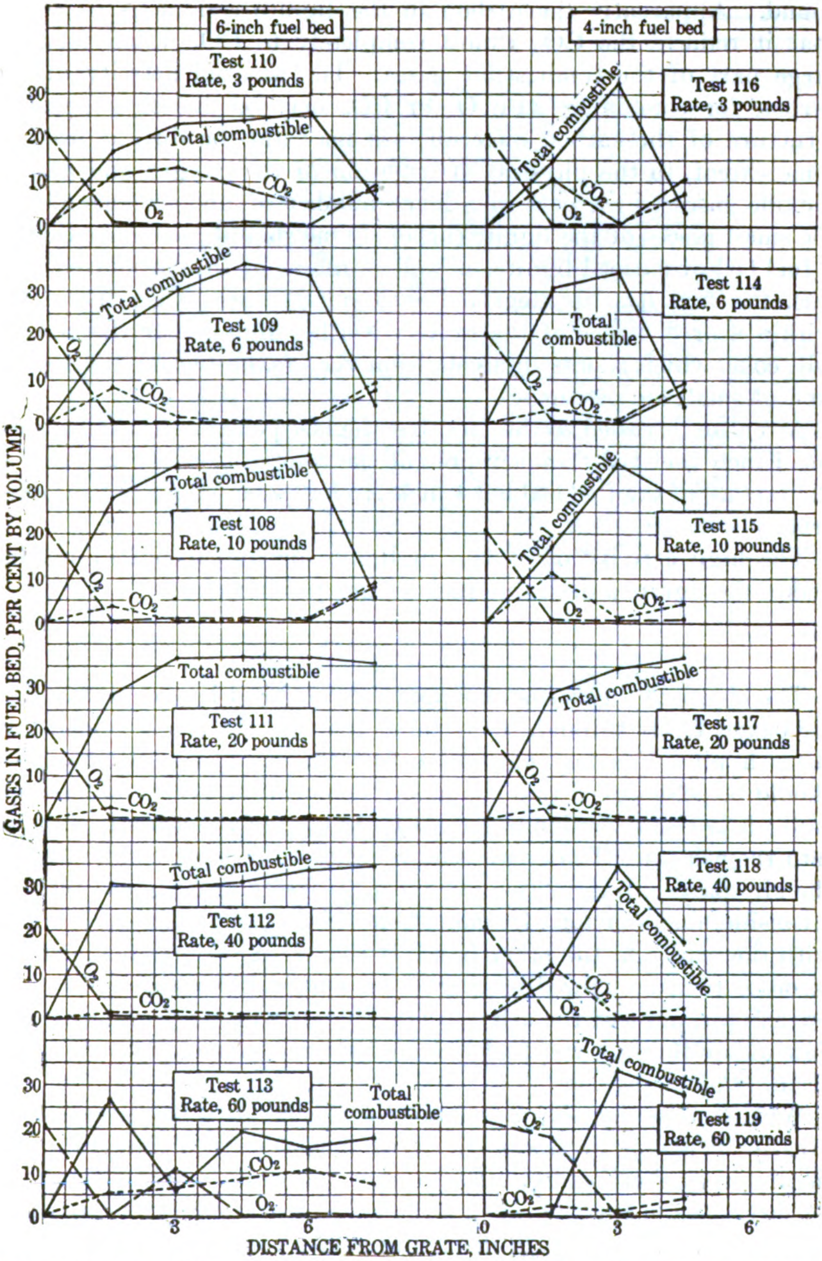

Figure 6.—Composition of gases in 4-inch and 6-inch fuel beds when the carbonized residue of lignite is burned at rates of combustion of 3, 6, 10, 20, 40, and 60 pounds per square foot of grate per hour. The last points of the 4-inch fuel bed charts are ½ inch above the surface of the fuel bed.

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no free oxygen (O_2) and practically no carbon dioxide (CO_2) is found. Apparently the carbon in the lignite residue is so active that it reduces the CO_2 almost completely to CO, which forms a large part of the combustible gases. The unusual activity of the carbon for combining with O_2 or CO_2 may be due to a peculiar structure of the carbon molecule. It may also be due, at least to some extent, to the physical distribution of the oxygen and carbon dioxide gases which pass in a large number of fine streams among the small pieces of the lignite carbon. One should remember that in a fuel bed of natural lignite, as well as in one of the carbonized residue, the fuel has disintegrated into small pieces when it reaches within 2 or 3 inches of the grate. Neither lignite nor the residue will coke, which results in a condition very favorable for the formation of small air passages.

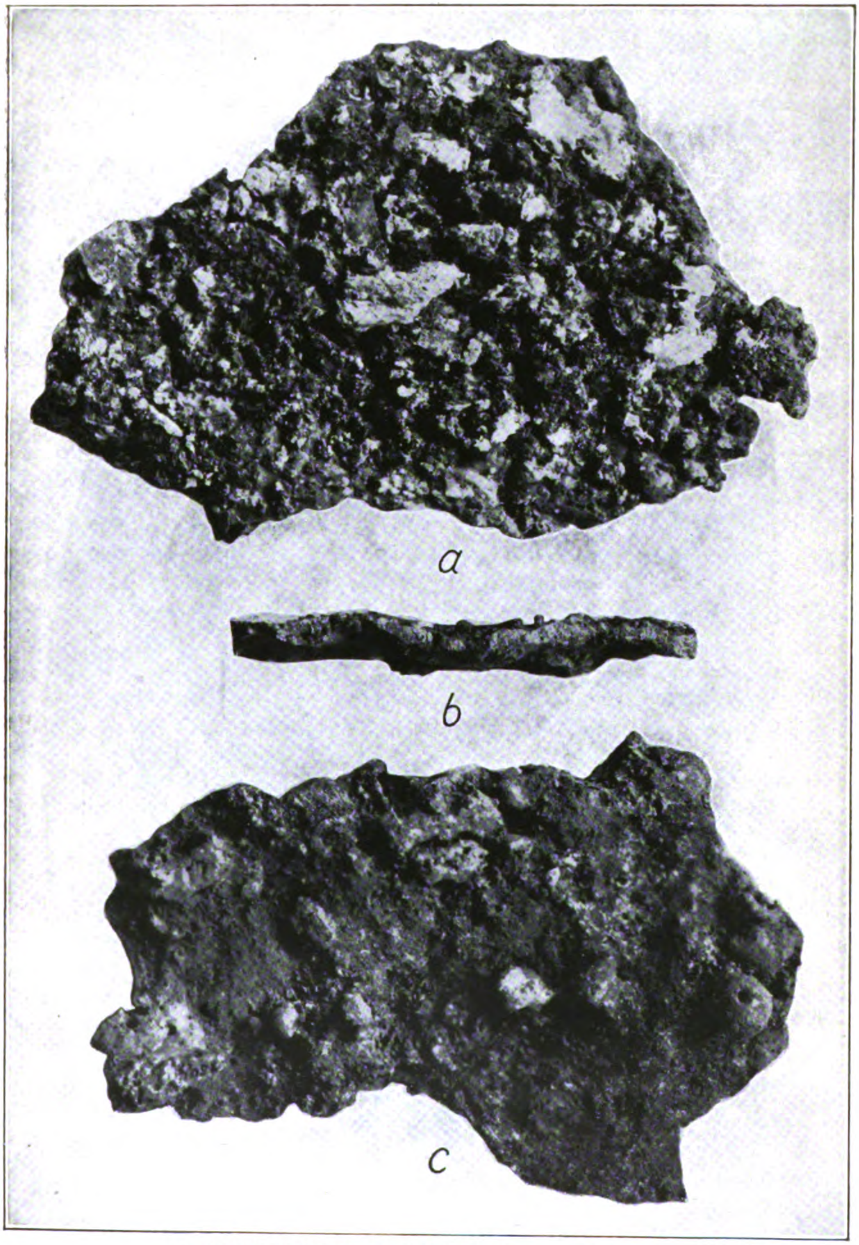
Attention is called to the fact that the last points on the curves for the 4-inch fuel bed do not represent the composition of the gases at the surface of the fuel bed but ½ inch from it, where oxygen has access from above.

The high activity of carbon in lignite or its carbonized residue makes the lignite a desirable fuel for gas producers.

DESIGN OF GRATE.

The object of a grate is to support the fuel bed in such a way that air passes freely through the burning fuel and the ash is voided into the ash pit. For any particular fuel the air spaces in the grate should be so designed that the loss of combustible is as small as possible; it is also desirable to have a large part of the ash sift through into the ash pit. These two requirements are always conflicting; if the air spaces are large the ash will pass freely into the ash pit, but a considerable amount of combustible sifts through the grate along with the ash. On the other hand, if the air spaces are made small, in order to reduce the dropping of incompletely burned lignite into the ash pit, most of the ash stays on the grate, thus preventing free flow of air through the fuel bed, and must be removed by frequent cleaning of the fire.

With lignite the difficulty from these conflicting requirements is greatly increased by the tendency of such fuel to disintegrate into small pieces that readily sift through the grate. When lignite is burned on an ordinary grate a large amount of combustible sifts into the ash pit. Therefore, in designing grates for burning lignite special efforts should be made to prevent this sifting. In grates No. 2 (fig. 3, p. 12) and No. 3 (fig. 4, p. 13) the problem is met by making the air spaces small. In grate No. 1 the air spaces were made large but at such an angle with the horizontal plane of the grate that unburned fuel dropped through only when the grate was shaken.



CLINKER FROM BURNING CARBONIZED LIGNITE.

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COMPARISON OF RESULTS FROM THE DIFFERENT GRATES.

The three grates (see figs. 2, 3, and 4) prevented sifting of combustible into the ash pit about equally well. With grate 1 the fuel bed could be cleaned of ash with comparative ease by slightly rocking the grate. Very little ash could be shaken through grate 2; most of it stayed on the grate, and with rates of combustion above 10 pounds fused into clinker. Results with grate 3 were somewhat better in this respect than with grate 2 but were not nearly so good as with grate 1. The residue clinkered more than the natural lignite. When burning the residue at rates of 20 pounds per square foot of grate area per hour and higher, a thin layer of solid impervious clinker was formed on the grate. With the natural lignite the clinker was porous and spongelike.

The clinker made by burning the carbonized residue is shown in Plate I. The appearance of the surface next the grate is shown at *a*, the upper surface, away from the grate, is shown at *c*, and the thickness and structure of the clinker is shown by *b*. The dense, solid structure, as shown at *c*, should be noted.

The results of an analysis of the clinker from the carbonized residue and of the free ash from lignite are shown in Table 6 following:

TABLE 6.—*Analysis of ash from lignite and of clinker from carbonized residue.*

Constituent:		Ash	Clinker.
Silica (SiO_2)	Per cent	38.6	35.9
Titanium oxide (TiO_2)	do	.8	.6
Aluminum oxide (Al_2O_3)	do	16.7	15.7
Total iron as ferric oxide (Fe_2O_3)	do	9.3	10.0
Magnesium oxide (MgO)	do	4.0	5.9
Calcium oxide (CaO)	do	13.4	22.1
Potassium oxide (K_2O)	do	.8	.9
Sodium oxide (Na_2O)	do	8.7	7.0
Total sulphur as sulphur trioxide (SO_3)	do	5.6	.8
Carbon dioxide (CO_2)	do	2.1	.1
Softening temperature	° F	2,000	2,000
Softening interval	° F	80	110
Flowing interval	° F	140	20

RELATION BETWEEN RATE OF COMBUSTION AND PRESSURE DROP THROUGH FUEL BED.

The relation between the rate of combustion and the pressure drop through the fuel bed is shown by the curves in figure 7. Points representing the same fuel and the same thickness of bed are connected by a curve and labeled.

The curves indicate that a fuel bed of carbonized residue offers much higher resistance to the passage of air than one of lignite, the resistance of a 4-inch bed of the former being considerably higher than that of a 12-inch bed of the latter. This higher resistance of the carbonized residue is undoubtedly due to its fineness. Fuel having such a high resistance as the residue can hardly be burned satisfactorily on a horizontal grate with natural draft. Even the natural

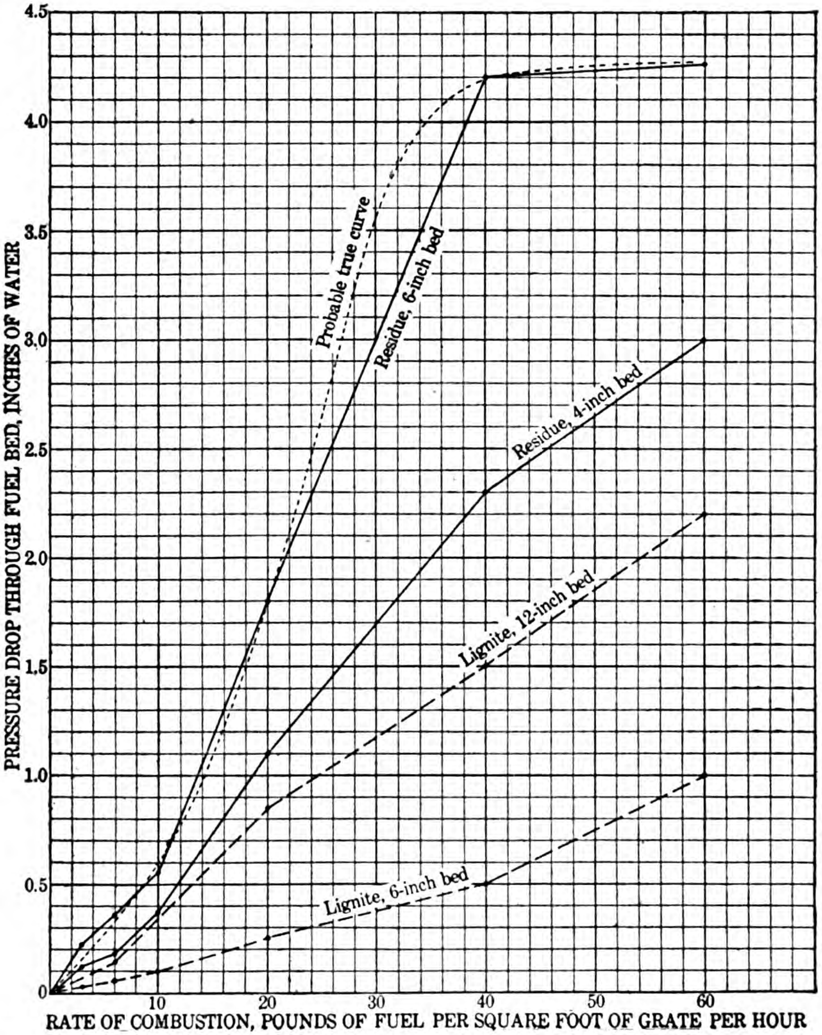

FIGURE 7.—Curves showing relation between the rate of combustion and pressure drop through fuel bed.

lignite offers higher resistance than bituminous coal of the same size, owing probably to the fact that the lignite crumbles in the fire.

The curve for the 6-inch bed of carbonized residue shows that the pressure drop through the fuel bed increases rapidly with the rate of combustion until the rate reaches about 40 pounds, the increase being very small for higher rates of combustion. This sudden change in the resistance to flow of air is caused by the agitation of the fuel that starts when the rate of combustion reaches about 40 pounds. The true curve of the pressure drop would probably have the shape shown by the smooth dotted curve. The curve for the 4-inch fuel bed of carbon residue shows similar changes of resistance, although not to such a degree as that for the 6-inch bed.

CONCLUSIONS FROM RESULTS OF SERIES *a* AND *e* TESTS.

The carbon in lignite and its residue, when these are burned, is very active in combining with oxygen and carbon dioxide. In burning these fuels on a horizontal grate in a hand-fired furnace, all the oxygen in the air rising through the fuel bed is used in combustion in less than 1½ inches from the grate. Above this point the CO_2 is rapidly reduced to CO, so that near the surface of the fuel bed there is no oxygen and very little CO_2. Inasmuch as the reduction of CO_2 to CO is a heat absorbing process, the surface of the fuel bed remains black at ordinary rates of combustion. The combustible gases rising from the fuel bed consist mostly of CO and H_2 with a small quantity of CH_4 and only traces of heavier hydrocarbons.

With lignite and its residue a comparatively high draft is required to burn 15 to 30 pounds of fuel per square foot of grate per hour. On account of the high draft necessary the air tends to blow through the fuel bed in channels and to cause an uneven fire. These statements are especially true of the carbonized residue.

TESTS (SERIES *b*) MADE FOR STUDYING COMBUSTION OF GASES RISING FROM FUEL BED.

DESCRIPTION OF FURNACE.

The tests of this group were made in a hand-fired furnace with a horizontal combustion chamber about 40 feet long. Figure 8 shows a vertical longitudinal section through the furnace. The grate is 5 feet wide and 6 feet deep, and is roofed with a fire-brick arch supported by the side walls. The combustion space is prolonged into a chamber 3 feet by 3 feet in cross section, lined with fire brick throughout. The furnace was provided with two tight-fitting firing doors. Air was supplied above the fuel bed in 20 jets, there being 7 in each side, and 6 in the front wall. The jets entered the furnace about 12 inches above the grate through nozzles 1¼ inches in diameter. Additional air was admitted through openings in the bridge wall. All this air was supplied under a pressure of 2 to 6 inches of water and was measured with orifices. The ash pit was closed and supplied with measured quantities of air under pressure. Provision was made for sampling the gases at the surface of the fuel bed, 12 inches from

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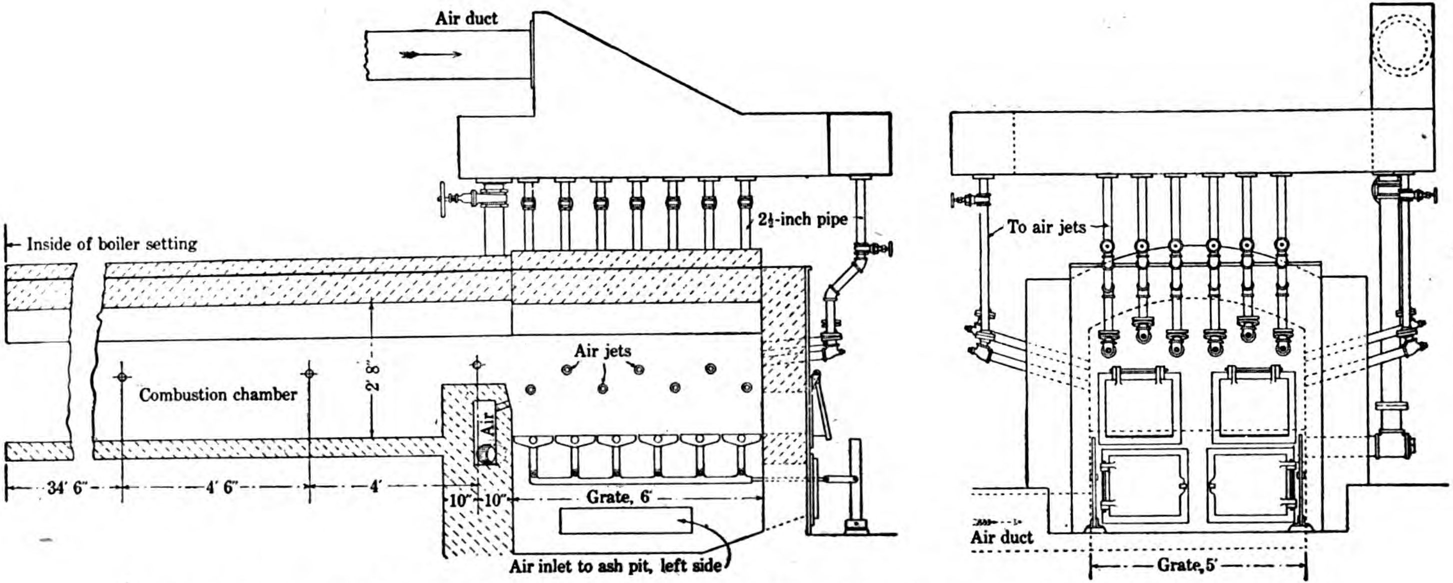

FIGURE 8.—Experimental furnace with a long combustion chamber for studying the combusion of gases rising from fuel bed.

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the fuel bed, above the bridge wall, and for each 5-foot length in the combustion chamber beyond the bridge wall. At the end of the combustion chamber the gases were discharged under a Heine boiler. The necessary draft was provided with an induced-draft fan.

METHOD OF RUNNING TESTS.

The furnace was heated to a bright red heat with Pittsburgh bituminous coal. The fire was then cleaned and enough coals left on the grate to start a fire with the lignite, which was broken by a hammer so that no pieces were larger than 4 inches across. Firings were made at 2½-minute intervals and a measured amount of air was supplied through the grate and over the fuel bed to obtain the desired rate and completeness of combustion. When the fire was in normal condition a set of simultaneous gas samples was collected for a period of 20 to 30 minutes. In order to get a fair average four to nine samples were collected at each cross section along the path of gases. At the section over the bridge wall, which was, on the average, 4 feet from the surface of the fuel bed, and at a section 33 feet from the surface of the fuel bed, separate gas samples were collected for 30 seconds before firing, and another set for 30 seconds after firing. At a section of 38 feet from the fuel bed instantaneous readings of CO_2 were taken every 15 to 20 seconds with an interferometer. All samples were taken with water-cooled gas samplers and were collected over mercury. Temperatures were measured with an optical pyrometer at a section 4 feet from the fuel bed. The analysis of the gas samples shows the progress of combustion of the gases along their path of travel.

TABLE 7.—*Results of tests of combustion above fuel bed.*

Test No.	Coal burned per square foot of grate per hour.	Air per pound of combustible through fuel bed, measured by orifice.	Air per pound of combustible over fuel bed, measured by orifice.	Total air fed to furnace per pound of combustible, measured by orifice.	Weight of air per pound of combustible, calculated from analysis of gases collected 33 feet from fuel bed.	Excess air, calculated from analysis,	Temperature at section 4 feet from fuel bed,
1	2	3	4	5	6	7	8
	Pounds.	*Pounds.*	*Pounds.*	*Pounds.*	*Pounds.*	*Per cent.*	° *C.*
341	31. 3	4. 73	7. 64	12. 37	13. 64	48. 1	1084
340	46. 9	4. 94	5. 31	10. 25	13. 77	49. 5	1024
342	60. 5	5. 51	8. 10	13. 61	13. 77	49. 5	1148

Table 8.—*Results of analyses of gas samples.*

TEST 340.

SAMPLES TAKEN CONTINUOUSLY OVER 32-MINUTE PERIOD.

Distance of section from fuel bed.	CO_2	O_2	CO	CH_4	H_2	Total combustible.
Feet.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
0	9.9	3.0	13.6	0.5	6.3	20.5
1	10.5	9.1	0.3	0.0	0.1	0.5
4	12.1	6.6	0.5	0.0	0.1	0.6
8	12.5	6.8	0.1	0.0	0.0	0.1
13	12.0	7.3	0.1	0.0	0.0	0.1
18	12.2	6.3	0.3	0.0	0.0	0.3
23	12.1	8.0	0.0	0.0	0.0	0.0
33	12.3	7.1	0.3	0.0	0.0	0.3

SAMPLES TAKEN AT INTERVALS DURING 30 SECONDS BEFORE FIRING.

4	11.8	8.0	0.2	0.0	0.0	0.2
33	12.2	7.3	0.0	0.0	0.0	0.0

SAMPLES TAKEN AT INTERVALS DURING 30 SECONDS AFTER FIRING.

4	12.7	6.1	0.2	0.0	0.1	0.3
33	12.7	6.3	0.2	0.0	0.0	0.2

TEST 341.

SAMPLES TAKEN CONTINUOUSLY OVER 36-MINUTE PERIOD.

0	10.0	2.4	14.1	1.0	10.3	26.7
1	9.4	8.5	2.3	0.1	0.6	2.9
4	13.1	5.8	0.9	0.0	0.1	1.0
8	13.3	5.5	0.7	0.0	0.0	0.7
13	13.2	6.2	0.1	0.0	0.1	0.1
18	13.9	5.4	0.0	0.0	0.0	0.0
23	13.4	6.4	0.0	0.0	0.0	0.0
33	12.6	6.4	0.4	0.0	0.0	0.4

SAMPLES TAKEN AT INTERVALS DURING 30 SECONDS BEFORE FIRING.

4	12.9	6.1	0.4	0.0	0.0	0.3
33	12.2	7.0	0.3	0.0	0.1	0.4

SAMPLES TAKEN AT INTERVALS DURING 30 SECONDS AFTER FIRING.

4	12.9	6.2	0.4	0.0	0.1	0.5
33	12.3	7.0	0.3	0.0	0.0	0.3

TEST 342.

SAMPLES TAKEN CONTINUOUSLY OVER 29-MINUTE PERIOD.

0	6.2	3.6	19.6	1.0	9.8	31.0
1	10.8	9.2	0.1	0.0	0.1	0.2
4	13.3	6.4	0.1	0.0	0.0	0.1
8	13.0	6.6	0.0	0.0	0.0	0.0
13	12.1	7.8	0.0	0.0	0.0	0.0
18	11.9	7.7	0.0	0.0	0.0	0.0
23	12.4	8.1	0.0	0.0	0.0	0.0
33	12.8	8.8	0.0	0.0	0.0	0.0

TABLE 8.— *Results of analyses of gas samples*—Continued.

TEST 342.—Continued.

SAMPLES TAKEN AT INTERVALS DURING 30 SECONDS BEFORE FIRING.

Distance of section from fuel bed.	CO_2	O_2	CO	CH_4	H_2	Total combustible.
Feet.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
4	12.4	7.4	0.0	0.0	0.0	0.0
33	12.0	7.7	0.2	0.0	0.0	0.2

SAMPLES TAKEN AT INTERVALS DURING 30 SECONDS AFTER FIRING.

4	13.7	6.0	0.05	0.0	0.05	0.1
33	12.6	7.5	0.0	0.0	0.0	0.0

RESULTS OF TESTS.

Three tests were made, all with the same percentage of air supply, but at three different rates of combustion. The results of these tests are given in Tables 7 and 8. The analyses of gas samples for each section of the furnace, given in Table 8, are the average for four to nine samples.

Column 3, Table 7, shows that only about 5 pounds of air can be forced through the fuel bed for each pound of combustible burned or gasified. The quantity of air supplied to the ash pit could be measured fairly accurately, so that the variation from the average for air admitted beneath the grate is small. The quantity of air supplied over the fuel bed could not be measured so accurately, because only the air supplied through the jets and the bridge wall was measured. Besides this measured air an appreciable quantity entered the furnace through the firing doors during the firing periods, although after each shovelful the door was quickly closed. The unmeasured air, the amount of which varied with the draft in the furnace, accounts for the difference of the values given in columns 5 and 6. The figures in column 3 show conclusively that less than one-half of the air needed for complete combustion can be supplied through the fuel bed, although the fuel bed was only 5 to 6 inches thick. That is, the fuel bed acts as a gas producer or fuel gasifier.

The analyses of the gas samples taken at the surface of the fuel bed show very high percentages of combustible. One should bear in mind that the jets of air blow over the surface of the fuel bed and that some of the combustible is burned before it enters the samplers. Furthermore, some of the air finds its way into the samplers and is particularly noticeable in the samples collected one foot from the fuel bed, the samplers in this position being just a little above the air jets. Therefore, the amount of combustible leaving the fuel bed is larger than the analyses of the gases show.

The analyses of gas samples collected at successive cross sections of the gas path show that combustion is practically complete 8 feet from the fuel bed, indicating that the volatile matter from the lignite is rather easy to burn.

Comparison of the analyses of the samples taken 30 seconds before firing with those of the samples taken 30 seconds after firing, shows that the distillation of the volatile matter was spread rather evenly over the entire firing cycle. This fact is clearly brought out by the curves in figure 9, which show the variation in CO_2 content in the flue gases during successive firing cycles when different coals were burned. The points in this figure were determined with an interferometer. The two curves at the top representing lignites show less variation than even those for anthracite.

Of the fuels represented in figure 9, the Pittsburgh coal shows the greatest variation in CO_2 content of the gases and is the most difficult to burn without producing smoke, because the rapid distillation of volatile matter after a charge is fired makes it difficult to supply enough air for a short period after the firing. The high moisture content of the lignite probably prevents, at least to some extent, rapid distillation after firing. However, results with partly dried lignite indicate that slow distillation is characteristic of lignite, and makes such fuel easy to burn without producing smoke.

DEDUCTIONS FROM TESTS MADE FOR STUDYING COMBUSTION ABOVE FUEL BED.

The distillation of volatile matter from lignite is distributed nearly uniformly over the entire firing period. The combustible rising from the fuel bed consists mostly of light gases which are easily burned without smoke. The main difficulty in burning lignite seems to be the slow ignition on account of the high moisture content.

TESTS (SERIES *c*) MADE FOR STUDYING THE RATE OF HEATING AND CHANGE OF APPARATUS OF LIGNITE IN FIRE.

When a piece of lignite is charged into a furnace the heat drives off first the moisture, with the volatile matter, from the surface layers. The loss of moisture and volatile matter causes cracking of the surfaces, thus exposing the interior of the piece to more direct action of the heat. As the heat penetrates into the piece the cracks become wider and deeper and small chips fall off. The edges, especially, are apt to fall off soon after the piece is thrown into the furnace. The cracking and crumbling may continue until the entire piece is reduced to a small pile of partly burned chips. Some of the

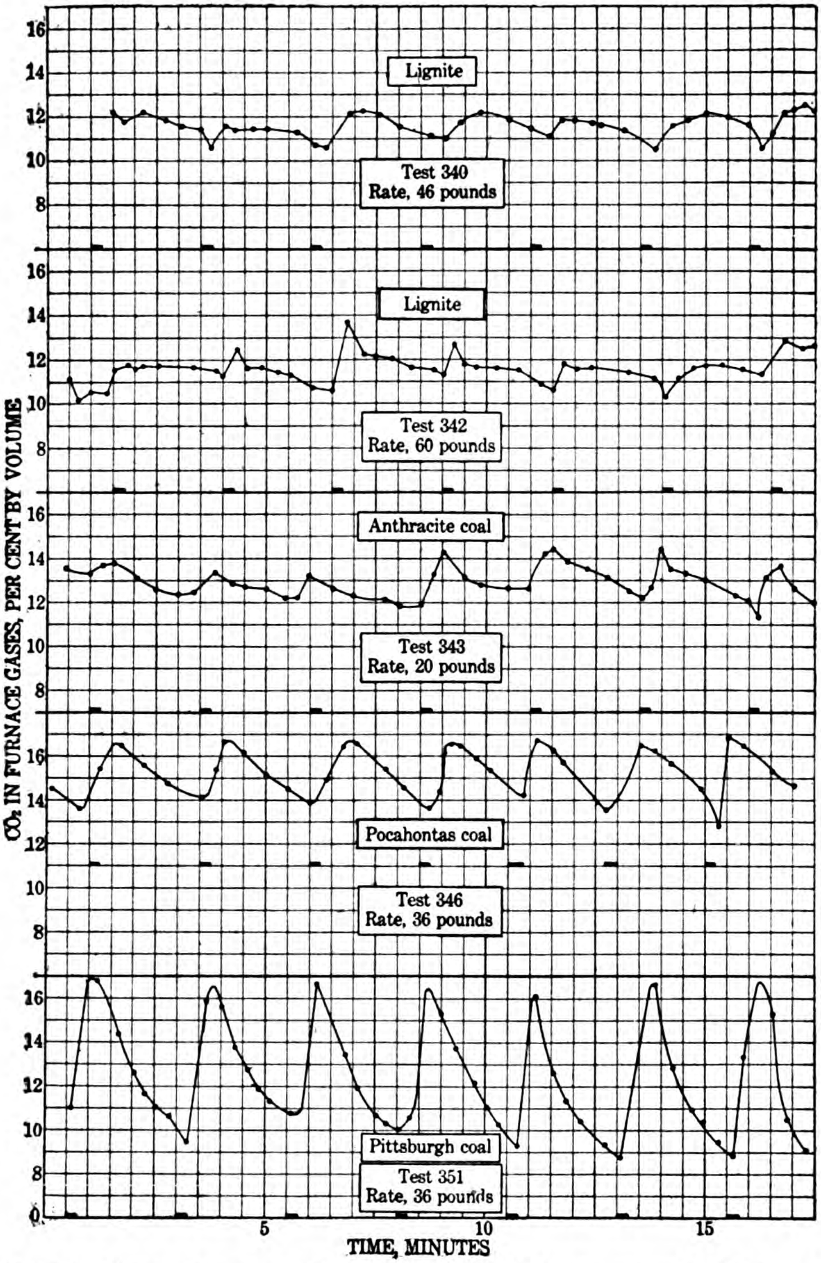

FIGURE 9.—Curves showing variations in CO_2 content during successive firing cycles when burning different coals. The black rectangles under each curve indicate the time taken for firing. Note the comparative absence of peaks in the curves representing lignite.

cracked pieces stay together for a long time if not disturbed. However, in all industrial furnaces there is some disturbance of the fuel bed; in a hand-fired furnace the impact of the fuel of each succeeding firing tends to disintegrate the cracked pieces; in a furnace having a mechanical stoker the motion of the grate bars or feeding plungers aids crumbling. Thus there seems little chance of keeping lignite from crumbling when burning it in industrial furnaces. The method of burning that causes the least disturbance of the lignite is the best one to use.

EXPERIMENTS WITH HEATING PIECES OF LIGNITE.

In order to observe closely the behavior of lignite when heated, small cubes of the lignite were placed in a small muffle furnace heated to about 850° C. A very small hole was drilled through each cube and a platinum thermocouple was drawn through the hole, the junction being placed in the center of the cube. The diameter of the thermocouple wire was 0.012 inch. Free access of air into the furnace was permitted, so that the volatile matter burned in close proximity to the cube and the heat developed by the combustion helped in heating it. Temperatures indicated by the couple were read every minute and the appearance of the cube was observed. Figure 10 shows the change in temperature in four such cubes. The following notes give the changes observed in the tests.

NOTES ON EXPERIMENTS.

Experiment 1 was made with a 1-inch cube. At the end of two minutes the corners of the cube became dull red and flames appeared. At the end of three minutes cracks began to form. At the end of four minutes the edges were cherry red and small pieces were chipping off. Cracking continued, but a large part of the cube stayed together until the end of 15 minutes. The remnants of the cube were then taken carefully out of the furnace and placed on an asbestos sheet. The temperature in the interior of the cube dropped to about 600° C., at which point it remained constant for some time. The surfaces of the piece were covered with ash, but through the cracks in this ash layer dull red was visible. Evidently enough air penetrated through the layer of ash to the unburned carbon to support a slow combustion, which maintained the temperature at about 600°. The ash prevented rapid dissipation of heat and helped to keep the piece hot. The temperature change at the center of this cube is given by the top curve of figure 10.

Experiment 2 was made with a 1-inch cube. The changes in temperature and in the external appearance of the cube were about the same as in experiment 1. At the end of 18 minutes the piece was taken out of the furnace and laid on an asbestos sheet. The

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temperature dropped to about 600° C., at which point it remained for more than an hour. This cube showed a small shrinkage with the grain of the layers but expanded about 50 per cent across the grain in accordion fashion. The general appearance of this piece after it was taken out of the furnace is shown in figure 11. The temperature change is shown by the second curve from the top in figure 10.

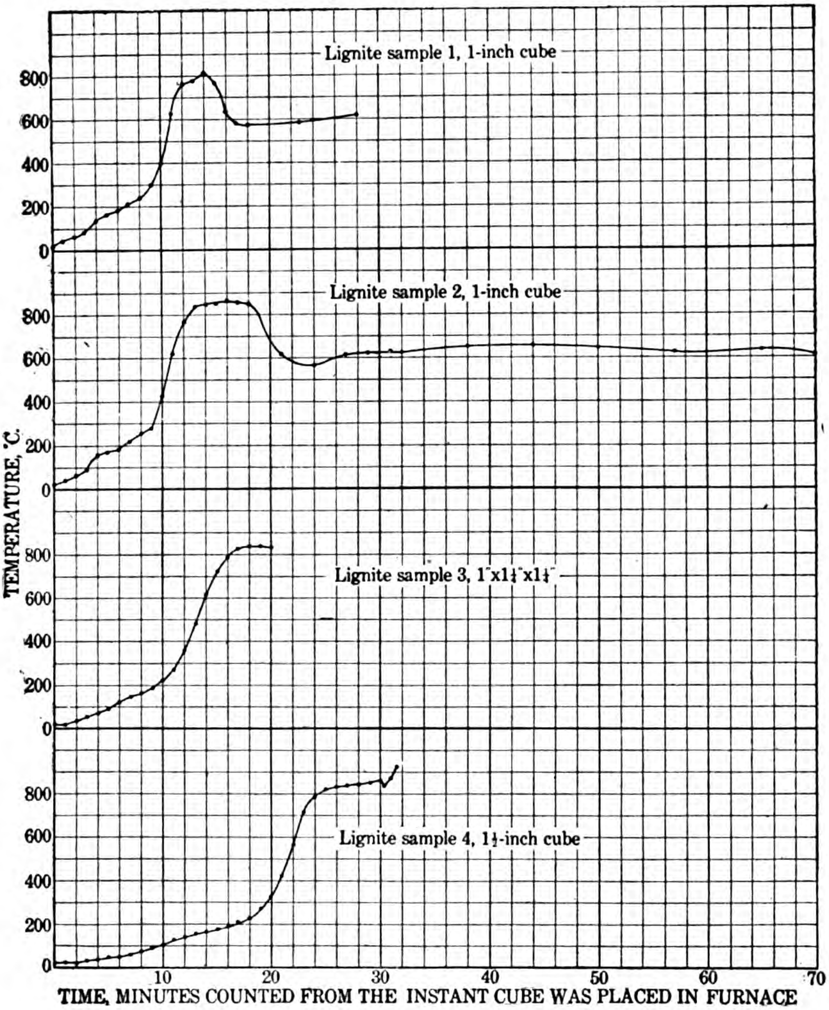

FIGURE 10.—Curves showing temperature rise in the centers of small cubes of lignite when placed in a muffle furnace heated to a temperature of 850° C.

Experiment 3 was made with a cube having 1¼-inch sides. The temperature change is shown by the second curve from the bottom in figure 10.

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Experiment 4 was made with a cube having $1\frac{1}{2}$-inch sides. The temperature change, shown by the curve at the bottom of figure 10, was slower but otherwise was similar to that of the smaller cubes.

These tests show that when a piece of lignite is charged into a hot furnace, the temperature of the piece begins to rise rapidly, when wide cracks are opened in it, permitting the heat to penetrate directly to the interior of the lump. This cracking, expansion, and crumbling when heated is characteristic of lignites, and is the main difference in behavior between lignite and bituminous coal in the furnace. Most bituminous coals fuse when heated, the lumps retain their original shape, and the slack coal fuses into a hard crust which may be cracked or broken into large pieces and thus virtually burns as lump coal does. This fusing of slack is called caking or coking of the coal. The fact that slack bituminous coal cakes does not mean that all bituminous coal makes metallurgical coke.

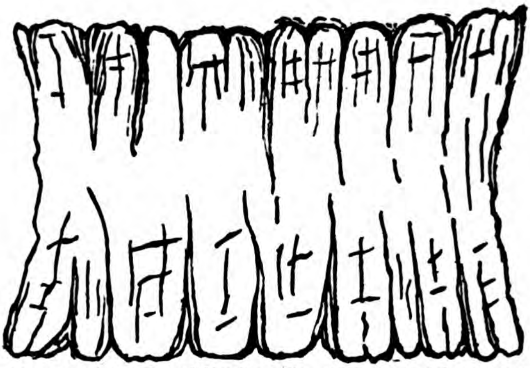

FIGURE 11.—Appearance of a cube of lignite after 15 minutes' heating in muffler furnace at temperature of 850° C. Drawn about twice the actual size.

DEDUCTION FROM SERIES *C* TESTS.

BURNING OF LIGNITE.

The North Dakota lignite cracks and crumbles easily when heated in the fire. This crumbling increases the resistance of the fuel bed to the flow of air, so that high draft is required to produce moderate rates of combustion. The crumbling also causes intense combustion near the grate where the air enters the fuel bed and, consequently, the fusion of ash into clinker. In an ordinary hand-fired furnace this clinker is difficult to remove without spoiling the fire and shaking much of the fine, disintegrated lignite into the ash pit. In fact, after cleaning, most of the fire is found in the ash pit with the ash, and only a few large lumps that have not been heated enough to disintegrate are left on the grate, but these are not hot enough to start a new fire. It is best to avoid any disturbance of the fuel bed as far as possible. The lignite burns with a clear yellow flame almost free from soot, and is very nearly a smokeless fuel, perhaps more so than the eastern Pocahontas coal. The drawbacks to burning lignite are: Difficult ignition, disintegration in the fire, high resistance to flow of air through fuel bed, sifting of combustible through grate, and clinkering.

BURNING OF CARBONIZED RESIDUE OF LIGNITE.

The lignite residue tested consists of small pieces and offers high resistance to the passage of air through even a comparatively thin fuel bed. Therefore, even for low and moderate rates of combustion, comparatively high draft is required to force enough air through the fuel bed. Such high draft is difficult to obtain without recourse to mechanical means, such as blowers and exhausters. The combustion is intense near the grate, producing high temperature and fusing the ash into a sheet of clinker impervious to air. It is difficult to remove the clinker without spoiling the fire and losing a large amount of the fuel into the ash pit. The best rate of combustion on a horizontal grate seems to be about 40 pounds of the fuel per square foot of grate per hour; at this rate the fuel bed is agitated by the blast and is thereby kept at a fairly uniform thickness. A large part of the ash is carried away with the gases so that the clinker accumulates more slowly than at the lower rates. This high rate of combustion has the disadvantage that part of the fuel is carried away with the gases as sparks. Low rates of combustion make a sluggish, uneven ignition of fire with the surface of the fuel bed black; the fuel is rather difficult to ignite, as is the building of fires with it.

REQUIREMENTS OF A FURNACE FOR BURNING LIGNITE AND ITS CARBONIZED RESIDUE.

Any furnace that will burn the lignite or its carbonized residue successfully must fulfill the following requisites:

(1) Provision must be made for rapid ignition.

(2) The furnace must be capable of supplying enough air with an ordinary draft to produce a reasonably high rate of combustion and make a hot fire.

(3) The grate must be of a design that will prevent sifting of combustible into the ash pit and at the same time permit cleaning of the fire without spoiling it.

TESTS (SERIES *d* AND *f*) WITH SPECIAL FURNACE.

DESCRIPTION OF FURNACE.

A special furnace was designed and constructed in accordance with the preceding requirements, and with particular application to

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house-heating purposes. The essential features of the furnace are shown in figure 12.

Rapid ignition is obtained by the use of a rear arch, which is nearly parallel with the plane of the grate and turns the hot gases and flames back over the fuel bed. Thus the incoming fresh fuel is heated not only by conduction through the fuel, or by radiation from the arch, but mainly by convection from contact with the hot gases and flames from the already burning fuel.

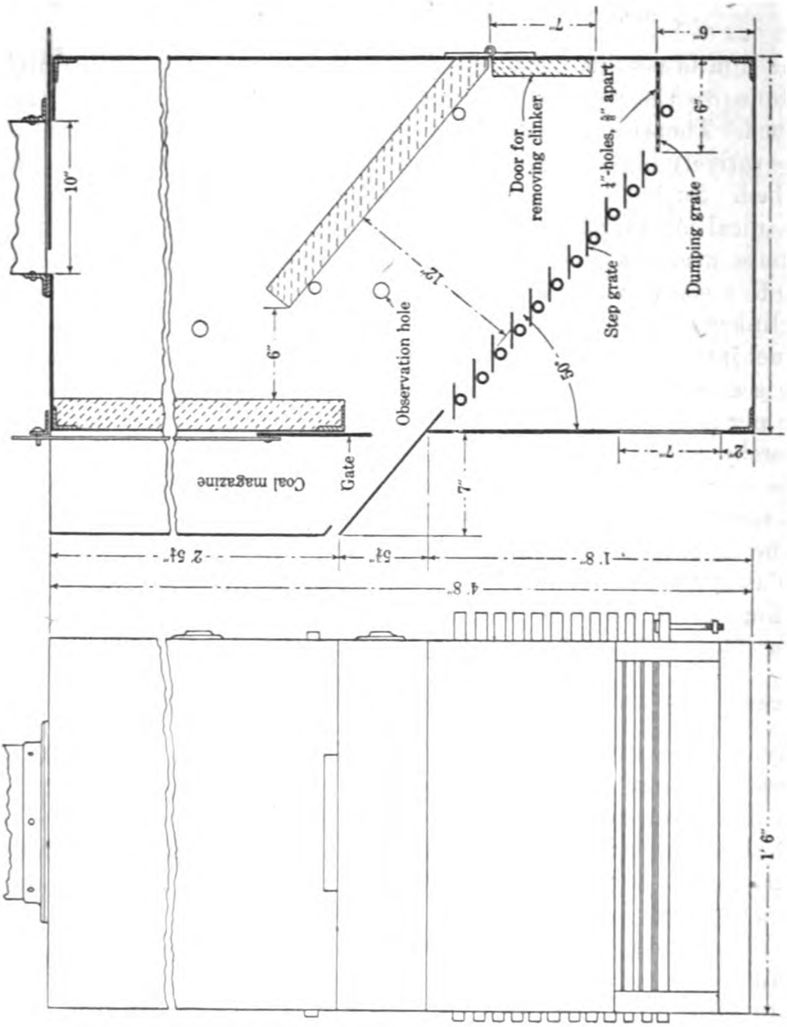

FIGURE 12.—Special furnace for burning lignite and its carbonized residue.

To heat lignite having 35 per cent moisture to ignition temperature takes more than twice as much heat as is required to heat bituminous coal containing 10 per cent moisture. Therefore it is difficult, if not impossible, to supply enough heat by radiation from the ordinary fire-brick arch to ignite the lignite. The rate of heat transmission by radiation depends almost entirely on the temperature. Hence, in order to supply more than twice the usual amount of heat by radiation from the arch, this would have to be kept at a considerably higher temperature for burning lignite than for burning ordinary bituminous coal. But with lignite it is not possible to obtain a temperature nearly as high as with bituminous coal. Thus it is evident that another factor in heat transfer must be brought into action, and that is heat transmission from the hot gases by convection.

The grate is inclined and has wide horizontal air spaces which can be easily kept open, permitting the free passage of air. Additional air is admitted through the door, for removing clinker, provided at the lower end of the grate. This air, in passing up between the arch and the fuel bed, sweeps the surface of the bed and helps greatly in burning or gasifying the fuel, thus making it unnecessary to force through the fuel bed all the air needed.

Experiments showed that the scrubbing action of the additional air caused rapid and rather complete oxidation at the surface of the fuel bed, indicated by the bright red heat which was practically absent in the tests made with the furnace shown in figure 1. Thus there were two oxidation zones—one next to the grate and one at the surface of the fuel bed—with probably a small reducing zone between them. Because the air that enters through the cleaning door against a low resistance burns or gasifies solid fuel, higher rates of combustion can be obtained with ordinary natural draft.

The air spaces in the grate, as mentioned previously, are horizontal, and the successive steps or grate bars overlap in such a way that no sifting of combustible into the ash pit can take place. The inclination of the grate is steep enough for the fuel to be fed from the magazine down the grate by gravity. The rate of feeding can be increased by slight agitation or rocking of the grate bars. The fuel does not cake, therefore the gravity feed is not interfered with by caking, as with most bituminous coals. Most of the ash slides down the stepped part with the fuel, and finally reaches the horizontal part of the grate, after most of the combustible has burned off. The horizontal part has small air openings through which the ash can be shaken into the ash pit. Any clinker that accumulates on this part can be removed through the cleaning door or by dumping the grate, without disturbing the fire on the inclined part.

The thickness of the fuel bed, and, to some extent, the rate of feeding, is controlled by the opening of the gate of the fuel magazine.

The furnace was provided with a sheet-iron chimney 10 inches in diameter and 25 feet high, set directly on top of the furnace.

RESULTS OF TESTS WITH SPECIAL FURNACE.

About a ton of the natural lignite was burned in this furnace, the tests extending intermittently over several weeks. Each test lasted two or more days. The fire was started by building a small wood fire on the horizontal part of the grate and covering the inclined part with a bed of lignite about 4 inches thick. As the flames from the wood fire passed over the bed of lignite, they set it afire, so that in less than an hour the lignite over the entire grate was burning. With a draft of 0.1 to 0.15 inch of water the lignite made a bright red fire, although the arch never became visibly red. There seemed to have been considerable combustion at the surface of the fuel, due to the air entering through the cleaning door and scrubbing the surface.

When the lignite was broken into pieces not exceeding about 2 inches in size, the feeding of the fuel was nearly automatic. With larger pieces the fuel had to be occasionally moved down by moving the grate bars or by poking the large pieces through the magazine gate. The fuel as it was burned contained a considerable amount of slack which, however, did not seem to cause any particular trouble.

Some clinker was found on and near the horizontal part of the grate. The clinkers were very porous and floated in the free ash, without touching the grate, and seemed to have been formed near the surface of the fuel bed. They were removed with a cleaning hook, and the fine ashes were shaken through.

With the draft nearly shut off the fire was kept burning without attention as long as 17 hours. At the end of this period a good fire was built in about half an hour. The fine fluffy ash which results from such slow combustion aids materially in holding the fire. On the whole, this furnace burned the lignite satisfactorily.

About 100 pounds of the carbonized residue was burned in this furnace. As far as can be judged from such a limited test, the residue gave much better satisfaction than the natural lignite. The residue, owing to the uniform size of the lumps, flowed down the inclined grate without any help and made a rather intense fire, entirely out of comparison with the sluggish fire obtained in the furnace shown in figure 1 (p. 11). The results of this test indicate that the carbonized residue when burned in this special type of furnace would make an excellent fuel for house-heating purposes.

RETENTION OF MOISTURE BY CARBONIZED LIGNITE.

As fuel is largely shipped in open cars, exposed to rain or snow, it is desirable to know how much moisture the carbonized lignite will retain after being wetted. To determine this property a sample of 700 grams, placed in a cylindrical tin vessel having the bottom punctured with numerous narrow slits, was completely immersed in water and soaked for 5 minutes. The can, with its contents, was then removed, permitted to drain until the dripping ceased, wiped dry on the outside, and weighed. The carbonized residue retained 23.6 per cent of its own weight of water. Before immersion the moisture content was 14.46 per cent, so that the total moisture was nearly 40 per cent. The carbonized residue was left in the vessel in the chemical laboratory and weighed from time to time. At the end of three days the added moisture was reduced to 14.5 per cent; at the end of 10 days, to about 10 per cent; and at the end of 14 days, to 5.5 per cent. Seemingly such material dries very slowly.

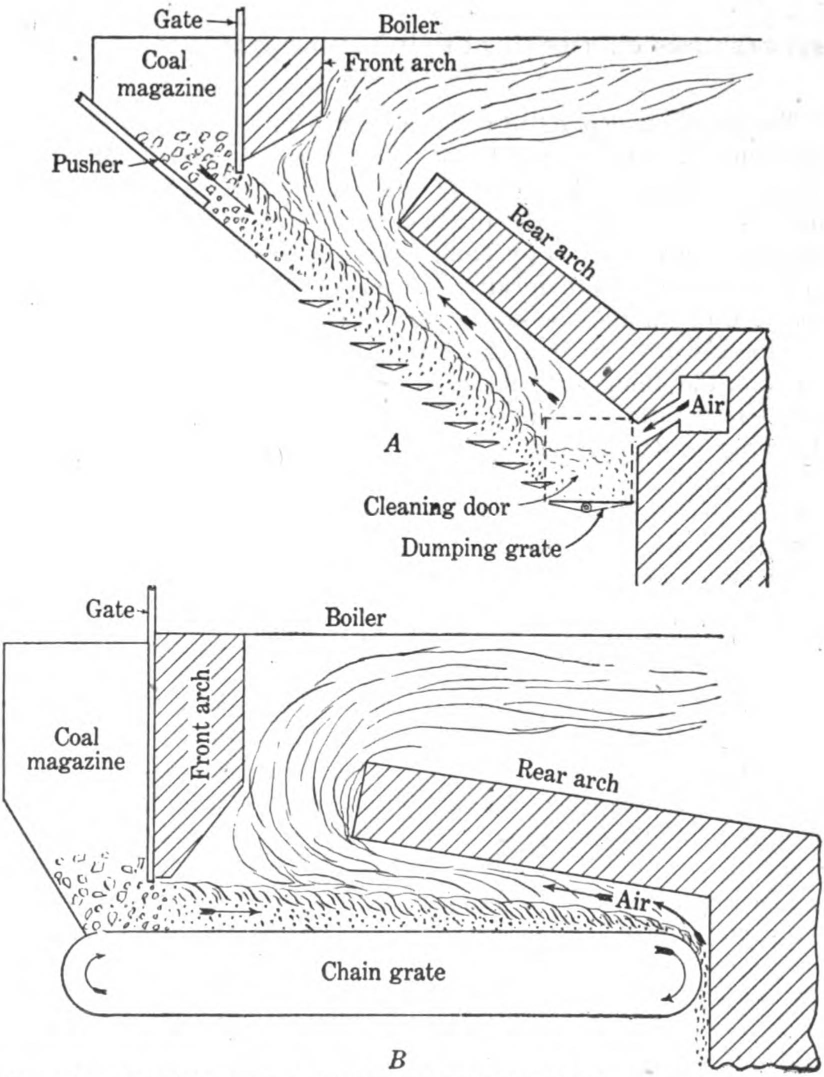

FIGURE 13.—Suggested design of boiler furnace for burning lignite and its carbonized residue.

The experiment was repeated with anthracite of the same size as the carbonized lignite. The anthracite retained 20.6 per cent of its own weight. At the end of a day the content of added moisture was reduced to 19.6 per cent.

These experiments indicate that the carbonized residue compares well with anthracite of the same size, and that it is a marketable product.

SUGGESTIONS ON THE DESIGN OF BOILER FURNACES FOR BURNING LIGNITE.

The principles embodied in the design of the special furnace shown in figure 12 can be applied to boiler furnaces with a promise of success. Diagram A, figure 12, showed a suggested design for an inclined step-grate boiler furnace. The fuel can be fed down the grate by gravity aided by hand regulation, or it can be pushed out of the magazine mechanically by a pusher plate. The horizontal air spaces between the step-grate bars can be kept open easily with a hand poker or by rocking the grate bars. The clinker, as it accumulated on the dumping grate, can be removed through the side cleaning door or can be dumped. The fine ash will accumulate on the dumping grate, through which it can be shaken into the ash pit. The air will be admitted through the horizontal air spaces between the step bars of the grate and through the special openings at the end of the grate. Probably two-thirds to three-fourths of the air needed for combustion should be introduced at the end of the grate, so that as the air passes between the fuel bed and the arch it will scrub the surface of the fuel bed and burn the fuel. The air enters the furnace against a very small resistance, so that a comparatively small draft will bring large quantities of air into the furnace and produce fairly high rates of combustion. The air entering through the air spaces between the grate bars has to pass through the fuel bed against a comparatively high resistance, and a high draft would be required to supply enough air in this way to gasify all the solid fuel.

The amount of air entering through the coal magazine or through the plate in front of the magazine, where the fuel is merely being dried and does not burn, should be kept as small as possible. The fire should be controlled by regulating the air admission at the end of the grate and not by admitting air through the magazine, because this air would not help in gasifying the fuel, but would merely aid in burning the gases rising from the lower part of the fuel bed. The gases rising from a fuel bed of lignite consist mostly of carbon monoxide and hydrogen, which are comparatively easy to burn, so that their combustion would be completed before they pass too far beyond the top of the arch. The comparatively narrow space between the rear arch and the front arch would help in mixing the air and combustible gases. A considerable amount of the fluffy ash would probably be carried with the gases. As soon as the gases pass beyond the contraction between the two arches they would expand and their velocity slow down, causing the ash to be deposited on top of and beyond the rear arch, so that comparatively little ash would be carried into the boiler flues.

The special openings for introducing air at the end of the grate would not fuse over, because they do not come in contact with the hot gases and the slag which the gases carry.

Diagram B, of figure 12, shows the application of these principles to a chain grate. The diagram shows the grate in a horizontal position, but it is believed that better results would be obtained if the top of the grate were inclined about 30 degrees to the horizontal.

The motion of the grate feeds the fuel into the furnace, and the thickness of the fuel bed is controlled by adjusting the opening of the gate. The air is introduced through the openings in the grate bars and in the rear of the grate, where the ashes are discharged into the ash pit. In this furnace the air that enters between the end of the grate and the bridge wall is used to burn the solid fuel on the grate. This air is made to pass between the arch and the fuel bed toward the front of the grate, and therefore aids both in the rate and the completeness of combustion, and is not detrimental to efficiency, as with the ordinary chain-grate furnace.

Provisions should be made to prevent air entering through the coal magazine and through the front part of the grate, where the lignite is being dried. When lignite is burned it is improbable that the furnace temperature will be high enough to injure the arch. With the carbon-dioxide content of the gases averaging between 13 and 14 per cent, the furnace temperature will not exceed 2,200° F., and if the top of the arch were exposed so it could radiate heat to the boiler above it, the arch would probably never get hotter than 2,000° F. There are plenty of refractory materials that will hold under such temperatures. For burning carbonized residue, which does not contain such high proportions of moisture as natural lignite, higher temperatures might be obtained. If these temperatures would be too high for the material in the arch, the latter could be constructed of special tiles suspended from water tubes, which could be made a part of the boiler. Similar construction is used on arches in locomotive furnaces. It should be borne in mind that, as the arches are inclined, only the horizontal component of the weight of the arch acts in pulling the arch down.

The two types of furnaces suggested can probably be used for burning low-grade fuels, other than lignite, which are difficult to ignite.

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Bulletin 76. United States coals available for export trade, by Van. H. Manning. 1914. 15 pp., 1 pl.

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Technical Paper 98. Effect of low-temperature oxidation on the hydrogen in coal and the change of weight of coal in drying, by S. H. Katz and H. C. Porter. 1917. 16 pp., 2 figs.

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Technical Paper 133. Directions for sampling coal for shipment or delivery, by G. S. Pope. 1917. 15 pp., 1 pl.

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Technical Paper 148. The determination of moisture in coke, by A. C. Fieldner and W. A. Selvig. 1917. 13 pp.

Technical Paper 170. The diffusion of oxygen through stored coal, by S. H. Katz. 1917. 49 pp., 1 pl., 27 figs.

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Bulletin 23. Steaming tests of coals and related investigations, September 1, 1904, to December 31, 1908, by L. P. Breckenridge, Henry Kreisinger, and W. T. Ray. 1912. 380 pp., 2 pls., 94 figs. 50 cents.

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